International Conference on Space Optics—ICSO 2018

Chania, Greece

9–12 October 2018

Edited by Zoran Sodnik, Nikos Karafolas, and Bruno Cugny

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International Conference on Space Optics — ICSO 2018, edited by Zoran Sodnik, Nikos Karafolas, Bruno Cugny, Proc. of SPIE Vol. 11180, 111805E · © 2018 ESA and CNES · CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2536113

Analysis of Pulse Position Modulated Fiber-Based Laser Systems for Deep Space Optical Communication

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ABSTRACT

Fiber-based laser sources delivering optical pulses at a wavelength of ~1.5µm have attracted a great interest in recent years mainly due to their unique properties. High efficiency, high output power, eye-safe wavelength and very good output beam quality make them a perfect tool for Free Space Optics communication. The most suitable modulation scheme for long-haul communication is pulse-position modulation mainly due to its high peak-to-average power ratio. In this paper we discuss a potential use of high power fiber laser system built in Master Oscillator Power Amplifier architecture for pulse-position modulated Deep Space Optical Communication. We focus on power scalability, beam quality, laser driver simplicity and temporal deformation of nanosecond laser pulses as well. In summary we shortly compare features of pulse-position modulated fiber laser transmitter with other high power laser sources being used in optical communication.

Keywords: Deep Space Communication, Pulse-Position Modulation, Free Space Optics, Fiber Lasers

1. INTRODUCTION

Deep Space (DS) communication plays an important role in space exploration programs, especially in interplanetary flights projects. This topic gained much interest after last announcements of manned Mars mission plans[1]. A high speed and reliable communication system would become critical for mission success. Unfortunately, long-haul communication is an extremely difficult task mainly due to beam spreading with the square of the distance. Moreover, a downlink transmitter has often tight power constraints - as an effect of limited access to the fuel, so high efficiency technologies are desired. Low volume and mass requirements, resulting from the high lunch cost, are also challenging[2].

Currently, in DS communication radio frequency (RF) and microwave links are used. A growing capacity demand has led to a frequency shift from S-band (used in 1960s and 1970s) to Ka-band. It enabled increasing the data throughput and size reduction of communication modules. Radio frequencies have a number of advantages, such as technology maturity and low atmosphere attenuation. The Deep Space Network (DSN) is currently the most advanced and sophisticated ground system for data exchange with long-haul space probes. It uses uncompromising solutions, such as very large antennas (70m and 34m in diameter) or liquid helium cooling system for low-noise amplifiers. On the other hand, radio frequency capabilities are limited and the effort put in this technology development is no longer adequate to the capacity gain[3,4].

A significant performance improvement can be achieved by shifting a carrier frequency up to the optical region of the spectrum. Comparing with conventional RF communication a laser beam spectrum is significantly narrower, so radiation intensity at the receiver is much higher. Moreover, the telescope diameter can be much smaller than RF antenna. An optical spectrum is still license-free and there are no bandwidth limitations. Thanks to the strong development of the terrestrial fiber based communication, off-the-shelf devices with excellent performance (such as high speed lasers or high sensitivity photodiodes) are now widely available. Optical wireless communication terminals meet mass, volume and power requirements as well. DS optical communication is a promising technology for long-haul, high speed, reliable communication[4].

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Despite the advantages, optical communication still faces challenges to overcome. Absorption losses, scattering, weather sensitivity or background noise are only examples of them. To improve the performance of the optical link, some mitigation techniques can be implemented on a various stages. For example, in physical layer a proper modulation scheme can solve a problem of atmosphere turbulences[5].

The most promising modulation format for DS communication is pulse-position modulation (PPM). Thanks to the high peak-to-average power ratio (PAPR), the average-power efficiency is improved. Moreover, this scheme is easy to implement and an adaptive threshold is not required in the receiver. A poor bandwidth efficiency is improved by using various variants of the PPM, such as differential PPM (DPPM), pulse interval modulation (PIM), etc. Regardless of the implemented variation, the idea stays the same – information is encoded in time intervals between pulses[4-6].

In last 20 years a number of spaceborne optical communication demonstrators have been performed. Most of them used neodymium (Nd) based solid state bulk lasers emitting at 1064nm pumped by laser diodes. The main advantage of this solution is high efficiency and technology maturity. In the last decade fiber laser technology has been strongly developed and it is becoming a great alternative for currently used solutions. Output power of fiber lasers may reach multi-kilowatt level and it is fully scalable. A thermal management is much easier due to high surface-to-volume ratio of an active medium. In a properly designed laser system, a diffraction-limited beam (M^2 = 1) is achievable[7]. From the space qualification point of view, fiber lasers are light, compact and having robust constructions.

In this paper a potential use of pulse-position modulated fiber-based laser systems in Deep Space communication is analyzed. A basic fiber laser in Master Oscillator Power Amplifier (MOPA) topology with directly modulated seed laser diode is considered. The authors wish to place a great emphasis on effects of dynamically changing pulse interval on the laser system output signal. In summary advantages and weakness of this technology as well as suggestions for future improvements of the considered laser systems are discusses.

2. PULSE-POSITION MODULATION FUNDAMENTALS

M-ary pulse-position modulation (M-PPM) is a modulation scheme that each symbol interval is divided into M time slots and a pulse appears only in one slot while the rest are kept empty. The capacity of M-PPM signal with τ_s time slot and peak-to-average power ratio can be calculated using formulas (1) and (2), respectively. In Figure 1 the capacity versus time slot duration for different orders of modulation are plotted. A higher PPM order reduces data rate, but, on the other hand, the PAPR parameter increases.

$$C = \frac{\log_2 M}{M\tau_s} \tag{1}$$

$$PARP = M \tag{2}$$

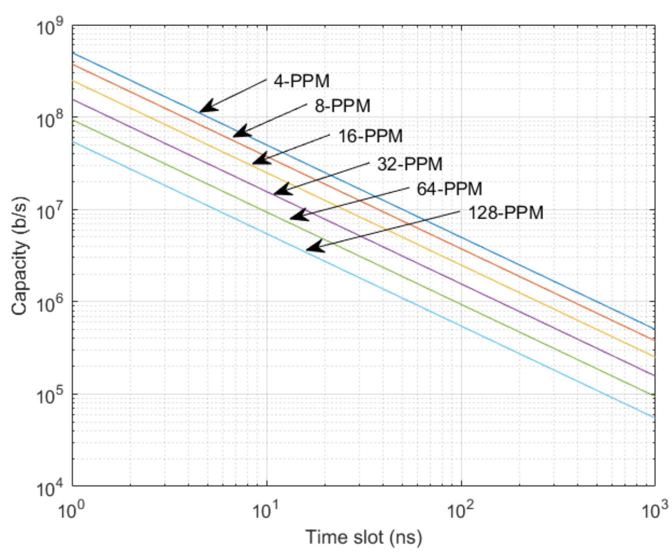

Figure 1. Capacity versus time slot duration in M-PPM.

To increase the bandwidth efficiency, different variants of the pulse-position modulation are implemented. In differential PPM the data is encoded in the intervals between consecutive pulses[8]. As a result, a symbol frame has different length and it depends on the symbol itself. In this scheme an additional guard time after every pulse is implemented. It decreases the total capacity of the transmitter, but it gives time to laser source to recover. A comparison of classic PPM and DPPM is presented in Figure 2. The capacity of DPPM and PAPR parameter is described by formulas (3) and (4), respectively[5].

$$C = \frac{2\log_2 M}{(M+1)\tau_s} \tag{3}$$

$$PARP = \frac{M+1}{2} \tag{4}$$

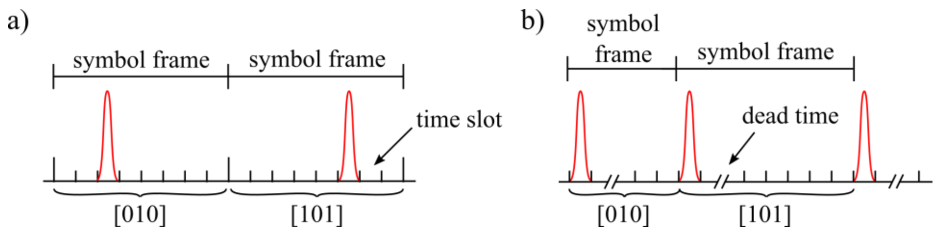

Figure 2. Comparison of various pulse-position modulations; (a) classic PPM (b) differential PPM.

The presented modulation variant is only an example of parameter improvement by simple modification of the classic PPM. More sophisticated methods like for instance pulse interval modulation (PIM) or overlapping pulse-position modulation (OPPM) are described in the literature.[5]

From the fiber laser engineering point of view, the generation of PPM optical signal is quite challenging. Most of the pulsed laser systems are optimized to work with constant pulse repetition rate[7]. It helps to reduce distortions of the signal as an effect of active medium saturation. Moreover, long time intervals between subsequent pulses can raise an amplified spontaneous emission (ASE) level, which leads to signal-to-noise ratio decrease.

3. FIBER LASER IN MOPA TOPOLOGY

Fiber lasers are coherent light sources based on optical fibers. In these lasers rare-earth-doped fibers play a role of gain media pumped by fiber-coupled laser diodes. Recently, erbium-doped fiber lasers operating at ~1550-nm-wavelength have been strongly developed, which is a consequence of applications in optical communication systems (third transmission window). Unlike many solid-state bulk lasers, fiber lasers have excellent beam quality factor, even the ones used in high power devices. Moreover, all-fiber designs are alignment-free, what makes them more reliable and shock insensitive.

High power fiber laser systems can be built in a master oscillator power amplifier (MOPA) format. This setup employs a low power injection seeder (as a master oscillator) and one or several amplifying stage to provide suitable gain (Fig. 3). The injection seeder properties determine properties of the whole laser system, such as repetition rate, pulse duration or output spectrum[7]. In general, an optical signal modulation can be obtained by direct current modulation of the laser diode or by using a continuous wave laser and an external modulator. The former solution is more power and cost efficient, however, in this approach it is hard to achieve a high speed signal. Moreover, temporal properties of directly modulated laser diode are worse when comparing with external modulation, mainly owing to gain switching process.

Fiber lasers in MOPA architecture are suitable for spaceborne free-space communication. Firstly, a properly designed laser system emits a beam with excellent quality factor. A broad access to off-the-shelf components and technology maturity of rare earth doped active fibers allows designing efficient and robust high power, all-fiber laser sources. The central wavelength of well-known erbium-doped fiber laser is placed in a transmission window of atmosphere. Furthermore, modular and alignment-free design meets the requirements of space-grade devices. The advantages of fiber lasers have been noticed by NASA, which planned to use an ytterbium-based fiber laser in MOPA architecture in Mars Laser Communications Demonstrator (MLCD) in 2000s[9].

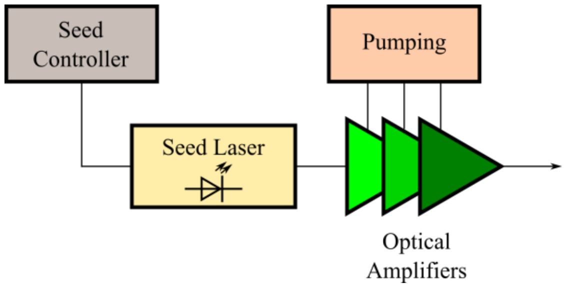

Figure 3. Block diagram of fiber laser built in MOPA architecture with directly modulated injection seeder.

Although low power fiber lasers operating in continuous wave (CW) regime have been successfully developed, a pulse operation is still a challenging task. The long length and small effective mode area of active fiber lead to a number of nonlinear effects, such as stimulated Brillouin and Raman scattering or self phase modulation. Moreover, a very important issue is pulse shape deformation being a consequence of medium saturation[10,11]. This phenomenon is described by the Frantz–Nodvick equation for rectangular pulse excitation[12] (5), where g_0 is medium gain per length unit, t_p is pulse duration, E_{in} is energy density and E_{sat} is saturation parameter.

$$P(z,t) = P_{in}\left\{1 - [1 - \exp(-g_0 z)]\exp\left[-\left(\frac{t - z/c}{t_p}\right)\right]\frac{E_{in}}{E_{sat}}\right\}^{-1} \tag{5}$$

Temporal distortion occurs when the relation between input pulse energy density E_{in} and saturation parameter E_{sat} becomes significant. If the medium is pumped with constant power, short input pulses will be less distorted. This theoretical conclusion is very important for telecommunication– pulse distortion in a fiber amplifier will not occur for a high-speed pulse-modulated input signal.

4. EXPERIMENTAL SETUP

The main aim of the experimental part of the study was the initial verification of pulse-position modulated high power fiber laser system as an optical transmitter. The emphasis was also put on the limitations identification of the laser system. The developed MOPA laser system consists of electronic laser driver with modulator, semiconductor laser diode based injection seeder and fiber amplifier (Figure 4).

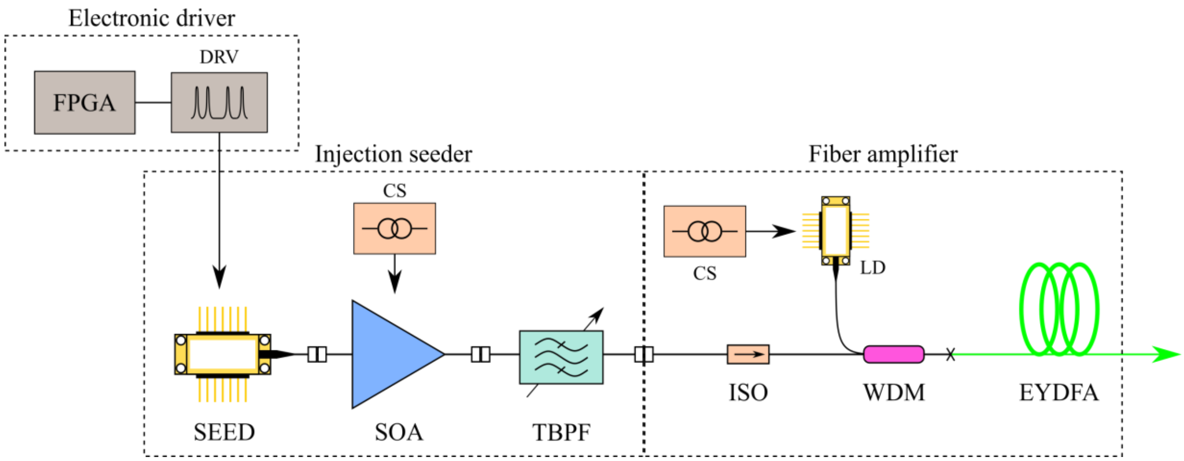

Figure 4. Block diagram of laser transmitter with fiber amplifier; DRV – laser driver, SEED – fiber coupled semiconductor seed laser, SOA – semiconductor optical amplifier, TBFP – tunable band-pass filter, ISO – optical isolator, WDM - wavelength-division multiplexer, EYDFA – erbium:ytterbium doped fiber amplifier, LD – pumping laser diode, CS – constant current sources.

The modulated signal is generated in the Altera Cyclone V FPGA device. The specially designed software lets to generate any M-order PPM and DPPM signal. Time slot width depends on adjustable phase-locked loop frequency f_{PLL}. To verify if a pulse interval changes the properties of output signal, the software sweeps over every possible code word (for M order modulation there is 2^M words). The FPGA output signal is passed to the high speed laser driver with a temperature controller. In this setup, a distributed feedback (DFB) high speed telecommunication laser diode with a central wavelength of 1547.3nm and a 4GHz analog bandwidth is used. Optical signal waveforms for single data sweep and for different orders of DPPM are presented in Figure 5. For further investigations a DPPM modulated sweep signal will be used, because it can cover all possible pulse intervals.

A semiconductor optical amplifier (SOA) plays a role of preamplifier and it was used to compensate peak power fluctuations of the seed laser pulses. A narrowband band-pass filter was applied to attenuate an amplified spontaneous emission of SOA. An optical isolator protects injection seeder components from amplifier's back oscillations. The erbium:ytterbium-doped fiber amplifier (EYDFA) is pumped by a 976-nm-wavelength laser diode controlled by an adjustable current source.

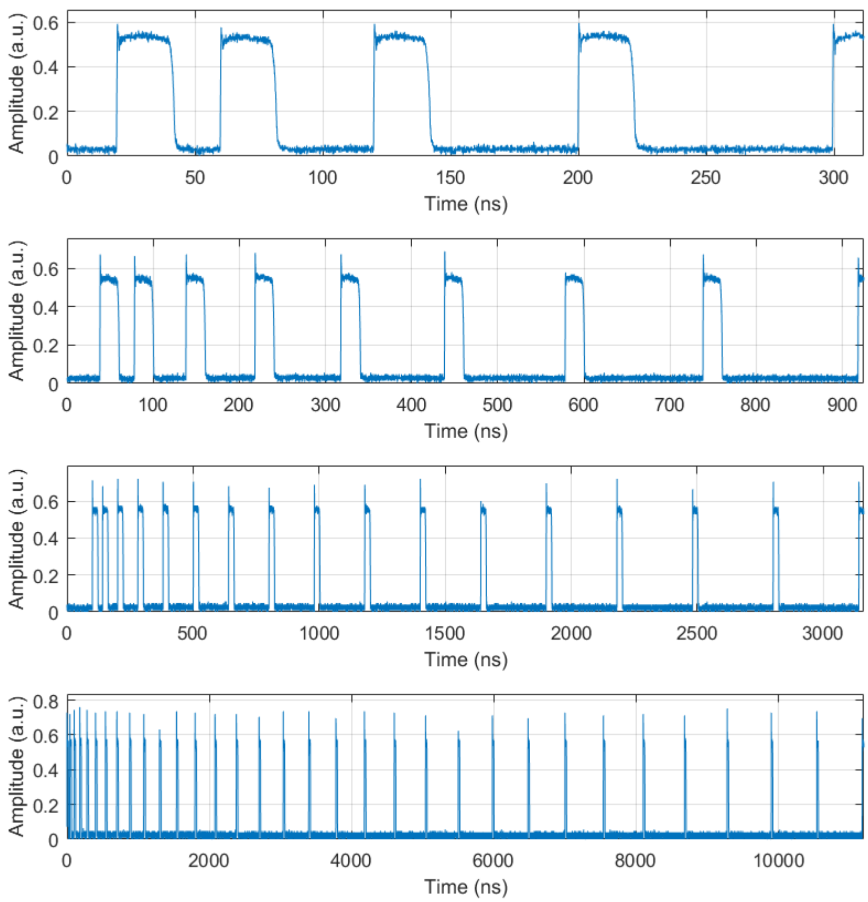

Figure 5. Output signals from the seed laser diode recorded for different orders of DPPM modulation (f_{PLL} = 50MHz, t_p = 21.8ns).

Time-based characteristics were measured with a high speed oscilloscope Tektronix DSA70604 with 6GHz bandwidth and an optical-to-electrical converter EOT ET-5000 (28ps minimum rise time). To measure an output optical spectrum, an optical spectrum analyzer Yokogawa AQ6375 was used. Moreover, the quality of output laser beam was measured by means of the beam propagation analyzer with a pyroelectric profiler (Ophir, NanoModeScan), making measurements according to the ISO 11146.

5. RESULTS

Key temporal, spectral and spatial parameters of the presented fiber laser system were measured. Experiments were held for three sets of differential pulse-position modulation – 4, 8 and 16. Unless otherwise specified, the repetition rate of the PLL was set to be 200MHz. It corresponds to data rates of 106.6Mbps, 88.8Mbps and 62.7Mbps, respectively. During the testes, a special emphasis was placed on these features, which are crucial from DS optical communication terminal point of view.

5.1 Temporal properties of pulse-position modulated signal

To perform temporal measurements of the optical signal, a fiber end was directed towards the optical-to-electrical converter window. The distance between the laser system and the photodetector was adjusted to avoid inner photodiode saturation. The 4-PPM signal from the seed laser with 7.5 ns time slot (depicted in Figure 6a) was generated and amplified in the EYDFA. It can be noticed that the pulse shape and its width do not change significantly. A spike on the rising edge of the pulse (a result of gain switching in the semiconductor DFB laser) was smoothed out. A very low rising time of the pulse (<60 ps – limited by measurement setup) was preserved after amplification, which shows a wide bandwidth of the amplifier. The same effects were noticed for higher orders of modulation schemes.

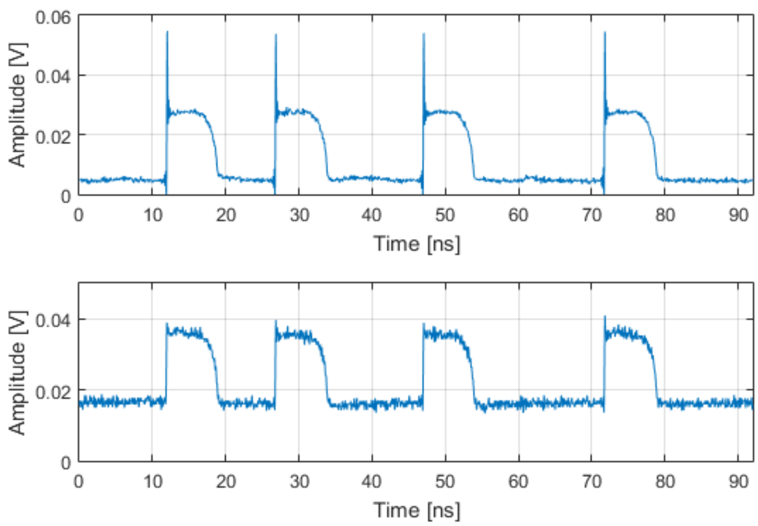

Figure 6. High-speed low-order PPM signal before (upper) and after (lower) amplification in EDFA (M = 4).

A significant pulse deformation, as an effect of active medium saturation, occurs for low speed signals, when the pulse width is high. To present this effect a 100ns rectangular pulse (f_{PLL} = 10MHz) was amplified in EYDFA (Figure 7). It can be noticed that the top of the pulse decreases exponentially in the time domain. In extreme cases, this effect may lead to significant pulse width shortening[10,11].

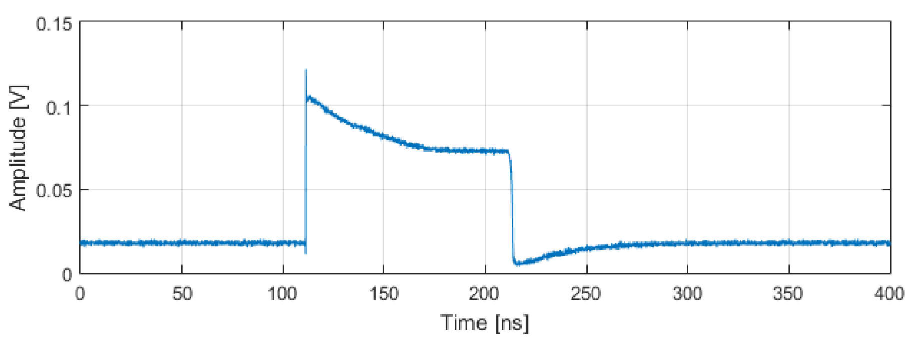

Figure 7. Distorted output pulse as an effect of active medium saturation.

5.2 Output power scalability

In the developed fiber-based MOPA system an output power can be easily adjusted by changing the pumping power of the fiber amplifier. In case of semiconductor laser pumping, output power of fiber laser can be changed by modifying the current of the pumping laser diode. Figure 8 presents an output optical power of the EYDFA versus current of the pumping laser diode. Injection seeder emits 8-DPPM sweep signal with 5ns timeslot (average optical power P_{in} = 22mW). It can be noticed that the relation between these two parameters is highly linear, directly showing that the system has a potential for further output power scaling-up. The output average power of generated pulse train was P_{out} = 420mW. The EYDFA gain was determined to be G_{max} = 12.8dB. Moreover, the current threshold I_{th} of the amplifier was determined to be I_{th} = 1.4A.

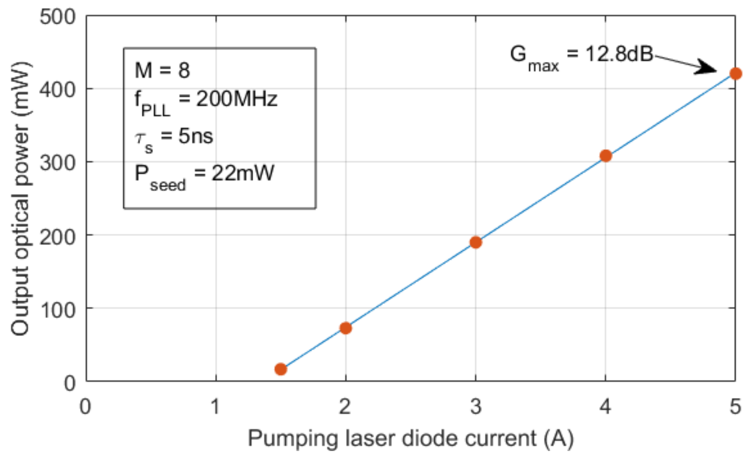

Figure 8. Output optical power of the fiber laser system versus the current of laser diode pumping the EYDFA.

5.3 Spectral characteristics

In the experimental setup the narrowband DFB laser diode operating at a central wavelength λ_c = 1547.3nm was used as a coherent light source. In Figure 9a a spectrum of this laser diode is presented. A periodic waveform just above the noise floor is typical for this diode construction and the signal-to-noise ratio is as high as 41.9dB. To compensate output pulse power fluctuations and amplify the signal, the SOA was used. This device has poor spectral properties resulting from the presence of amplified spontaneous emission (ASE), as shown in Figure 9b. To improve the injection seeder's spectrum, an additional narrowband filter was used. As a result, a narrow ($\Delta\lambda_{-3dB}$ = 0.28nm) spectrum with central wavelength λ_c = 1547.3nm and high signal-to-noise ratio SNR = 58.9dB were achieved. It has been also noticed that the output spectrum of the injection seeder does not change for different modulation orders.

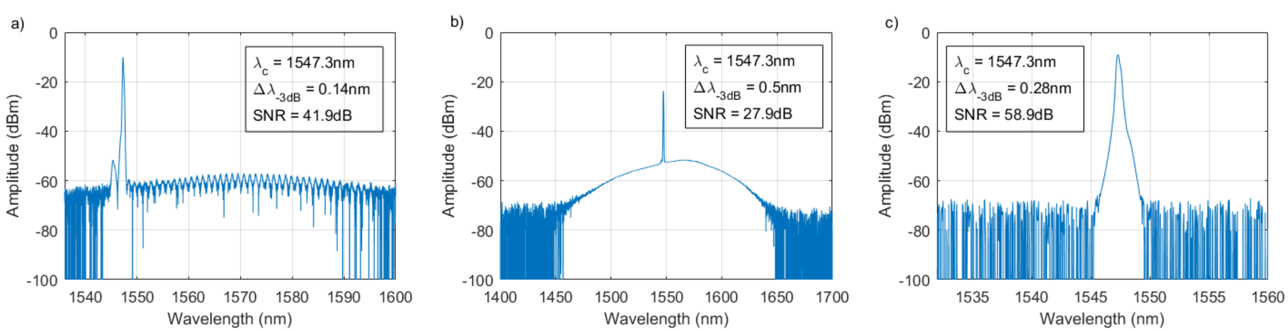

Figure 9. Output spectra of the DFB laser diode (a), semiconductor optical amplifier (b) and narrowband filter(c).

Figure 10 presents an output spectrum from the laser system for various orders of pulse-position modulations. The EYDFA was pumped with maximum available power (corresponding to the current of laser diode I_{LD} = 5A). It can be noticed that a wideband noise appears as a result of the ASE signal in the EYDFA. The signal-to-noise ratio increases for lower orders of PPM, which is a consequence of longer periods between pulses for long data words. In Figure 11 the output spectra for 8-PPM signal and various pumping power are presented. For higher current of pumping laser diode, the ASE level increases. However, it is worth mentioning here that ASE can be reduced by an appropriate laser system optimization (e.g. by selection of a proper length of active fiber).

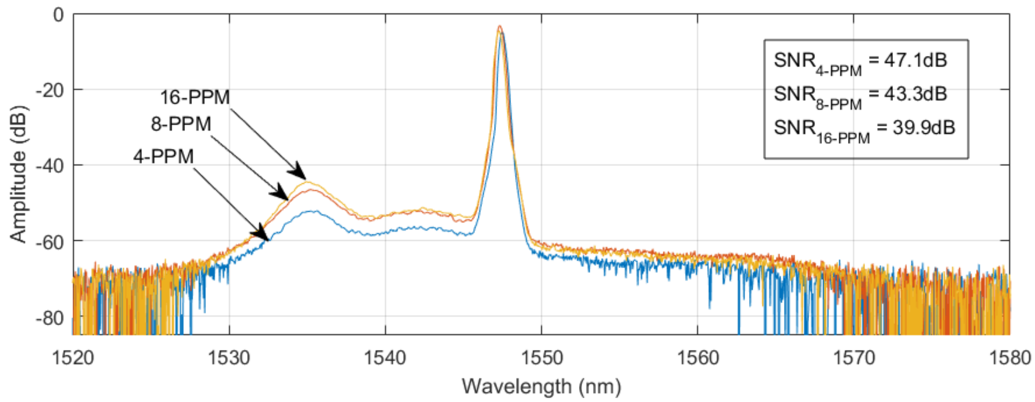

Figure 10. Output spectra for various orders of PPM.

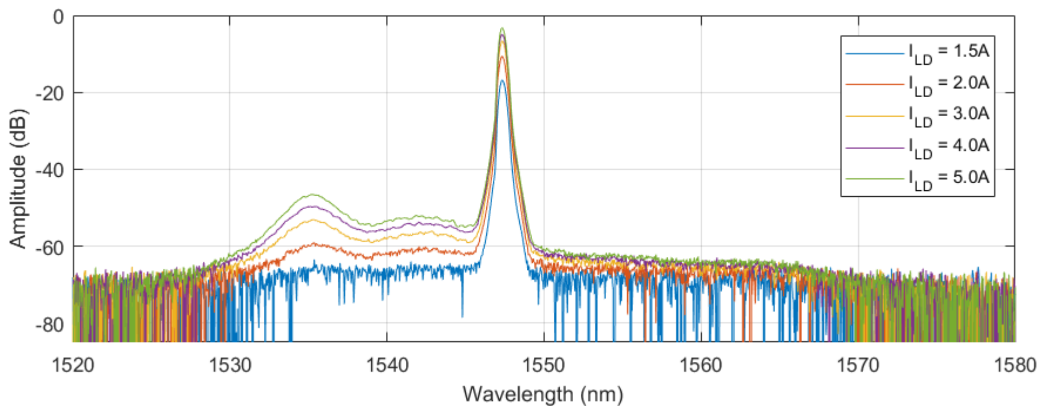

Figure 11. Output spectra for various pumping power ($M = 8$, $f_{PLL} = 200$MHz).

5.4 Output beam quality

Fiber lasers based on single mode fibers have very good spatial properties. This parameter is extremely important in DS communication, because high beam divergence leads to range shortening. The intensity profile of the output beam was measured with the use of a fully automated M^2 system. In the presented setup, a diffraction-limited beam with $M^2 < 1.05$ for both axes was achieved. The far field profile of the output beam is depicted in Figure 12.

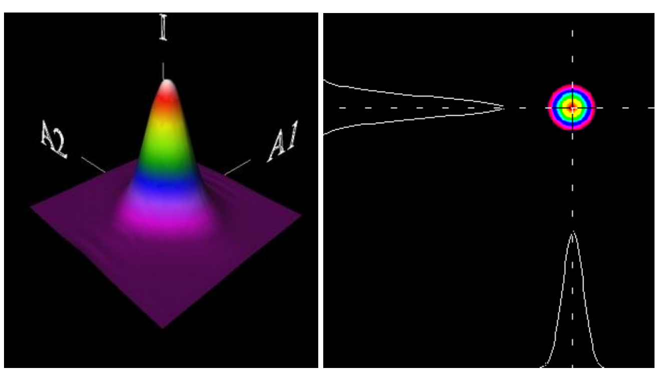

Figure 12. Far field profile of the output beam.

6. SUMMARY AND CONCLUSIONS

High speed and reliable Deep Space communication is a challenging task and well-known radio-based systems are no longer sufficient to carry the growing demand on the data capability. The problem may be solved by shifting the carrier frequency to optical region of the spectrum. Optical transceivers are able to transmit data in high speed for longer distance, due to lower beam divergence when compared with RF technology. Moreover, these systems met low mass, low power and low volume requirements for space equipment.

To maximize optical link performance a number of mitigation techniques are performed. One of them is selecting a proper modulation scheme. Theoretical works show that pulse-position modulation and its variants with matched encoding is a promising technique for long-haul transmission. The main advantages of this method are simplicity and high peak-to-average power ratio.

In physical layer of the optical link high power lasers with high output beam quality are required. Well suited laser systems for these applications are fiber laser systems built in a master oscillator power amplifier architecture. These devices can emit narrow, diffraction-limited optical beam required by long-haul communication. Transmitters built in all-fiber technology are light, shock-resistant and thermal management is easy to perform. These features make them a promising solution for spaceborne applications.

The paper presents an initial experimental analysis on how properties of 1.55 µm fiber-based MOPA system change if a seed laser generates pulse-position modulated optical signal. The achieved results show that fiber amplifiers smooth out input signal without changing overall shape of the nanosecond pulse. For long-duration pulses a fiber laser optimization is recommended because of saturation effect resulting in pulse distortion. The output optical power of the laser transmitter increases linearly with the rise of pump power, so it can be adjusted in an easy way. In our case the output average power was over 0.4 W. Spectral characteristics of the system are different for various orders of PPM. In the case of higher order modulation, signal-to-noise ratio decreases, as an effect of rising amplified spontaneous emission level. Noise level increases for higher pumping powers as well. The output beam was only diffraction-limited with M^2 <1.05, thus proving very good spatial properties of the fiber laser system. The results of the study show that modern high power fiber-based laser systems may become a great alternative for currently used coherent light sources in Deep Space optical communication.

ACKNOWLEDGMENTS

Authors would like to thank Mr. Eng. Marcin Mamajek and Mr Jan Karczewski for their technical assistance. This work was partly supported by the National Science Centre, under project No. UMO-2014/14/M/ST7/00868.

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